O White Space, White Space, *Whatfore* Art Thou White Space?

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***Abstract*—A few steps from Shakespeare's spiritual home The Globe Theatre in London, the UK regulator Ofcom is formulating its own well-crafted play based on TV White Spaces (TVWS). We have been leading a major trial under the Ofcom TVWS Pilot in the UK, where it is noted that the same approach to TVWS is employed across Europe through the ETSI EN 301 598 Harmonized European Standard. Our trial has led to numerous observations on white space availability, use cases, and achievable performance in TVWS particularly under aggregation scenarios, among other aspects. This paper expands on some of our prior publications highlighting such outcomes and observations, particularly based on real testing within our trial. It draws fundamental conclusions around scenarios in which TVWS could and should be used. For example, it is observed that TVWS is often most appropriate for below-rooftop receiver or indoor scenarios, and for lower-power (e.g., 20 dBm) deployment scenarios which achieve excellent, and far more consistent, usable channel availability than higher-power alternatives. Further, aggregation in TVWS is heavily covered, attempting to match to various example deployment cases mirroring current and future communication systems. Observations are made on radio design under aggregation, particularly for the European TVWS case.**

Keywords*—*TV white space, geolocation databases, field trials, spectrum aggregation, spectrum sharing

I. INTRODUCTION

Progress in TV White Spaces (TVWS) has been propelled forward initially by regulatory steps and deployments of White Space Devices (WSDs) in the US [1]. In addition to white space trials and developments elsewhere such as in Africa and Asia, Europe is proceeding with the finalization of rules and testing of TVWS technology on a large scale [2], [3]. The European progress is particularly driven by the UK regulator Ofcom's work and instantiation of a large pilot of WSDs and the underlying enabling technology [4]. All trials within this pilot must operate under Ofcom's prospective rules for WSDs, reflected in ETSI EN 301 598 [3]. The Ofcom TVWS Pilot serves wide-ranging purposes and objectives, including the assessment of the entire Ofcom TVWS framework and the associated ETSI EN 301 598 Harmonized European Standard [3], investigation of the potential for TVWS deployments, e.g., given TVWS availability and WSDs performance, and testing of the interplay between the stakeholders in TVWS operation, among others.

TVWS operates under somewhat different rules and assumptions depending on where it is deployed. For instance, in the US there is a fixed maximum allowed power given to WSDs, which means that in TV channels and locations where that power would only marginally violate interference limits at primary receivers the WSDs can't be used at all. While relatively simple, this leads to a vast reduction in the availability of TVWS such that in many large cities there is no TVWS available at all. In the UK and EU case, through ETSI EN 301 598, the allowed power of WSDs can be varied dependent on their location, channel, spectrum mask and other characteristics. This makes white space available even in the most challenging cases such as the immensely busy spectrum usage scenario in much of the UK, and the EU approach further allows WSDs even of poor spectrum mask to operate, through reducing the power that they are allowed to transmit due to the their associated greater adjacent channel leakages.

Given that a good wealth of experience is now out there in terms of testing and deployment of WSDs and various TVWS frameworks, now is a good time to take stock based on this experience to objectively investigate how TVWS can be used. This paper set out to achieve that objective within the construct of our trial within the Ofcom Pilot. This paper therefore particularly concentrates on use cases and availability/practicality of TVWS, and particularly looks at issues such as bounds to what can be achieved, e.g., by aggregation in TVWS. It builds on some of the past work we have published, for example, in [5], [6].

This paper is structured as follows. Section II identifies key characteristics of TVWS and WSDs that impinge on their usage scenarios. Section III undertakes a performance assessment of TVWS scenarios, based particularly on our trial within the UK Ofcom Pilot and the TVWS rules in the EU in general. Section IV concisely summarizes scenarios for TVWS/WSD usage based on the observations in Sections II and III. Finally, Section V concludes, also noting some important future-proofing observations.

II. KEY CHARACTERISTICS OF TV WHITE SPACE AND WHITE SPACE DEVICES

In assessing the appropriate use cases for TVWS, it is important to understand the key characteristics that constitute TVWS and the constraints that WSDs must abide by, and to analyze the implications of those. This section addresses such issues. It concentrates on US and EU regulations for TVWS, noting that most of the other deployments internationally employ similar rules (particularly to the US case).

A. *Fundamental Requirements on White Space Devices*

There are several basic requirements on WSDs which fundamentally affect the appropriate choices for their usage. A first requirements is that for the WSD to operate at all, it has to have GPS or some other form of guaranteed reliable geolocation capability. This is with the exception of those slave WSDs that intend to operate with only "generic operational parameters" in the EU case, although it is noted that such generic operational parameters usually imply extremely low maximum EIRP limits, in the majority of cases in the UK, at least. It is also with the exception of "sensing-only" WSDs in the US case, which may operate up to a maximum EIRP of 50 mW (17 dBm) based only on sensing to avoid causing primary interference through their operation. A further important exception is that Ofcom in the UK will allow the use of manually-configurable WSDs on a *licensed* basis, at least for a transitional period until more "automatic" (i.e., GPS-capable) hence license-exempt WSDs are available. This manual configuration is generally related to the input of location information to the device. A one-off fee of 1,500 GBP is charged for the license to each entity that wishes to deploy an unlimited number of manually-configurable WSDs.

Based on the EU or US rules, excluding "sensing-only" devices in the US case, it is required that all WSDs are within a network that has at least one GPS-capable or manually location-configured device (in the manually-configurable UK case) and with at least one device having Internet access to obtain allowed transmission parameters from a certified geolocation database (and, in the EU case, obtain a list of certified geolocation databases). It is not possible for a network of WSDs to operate without having Internet connectivity at some point.

1) *Implications*

Given these requirements, first, it is not possible to use TVWS for ad-hoc networks or scenarios where the WSDs (or at least one of the WSDs in the network) are not Internet connected. This means that you couldn't, for example, use TVWS to serve sensor, smart-grid or other scenarios where WSDs were perhaps monitoring in a network alone without Internet access, or for a direct (e.g., two-way radio like) communication between WSDs. In essence, all TVWS deployments must be infrastructure-based in some way, ultimately linked to the Internet. However, it is noted that the "slave" or "Mode 1" devices can generally communicate with each other, as long as they are obeying the rules for their particular geolocation. Hence, it is possible to extend a conventional base station and terminal (hub and spoke) network with multiple hops.

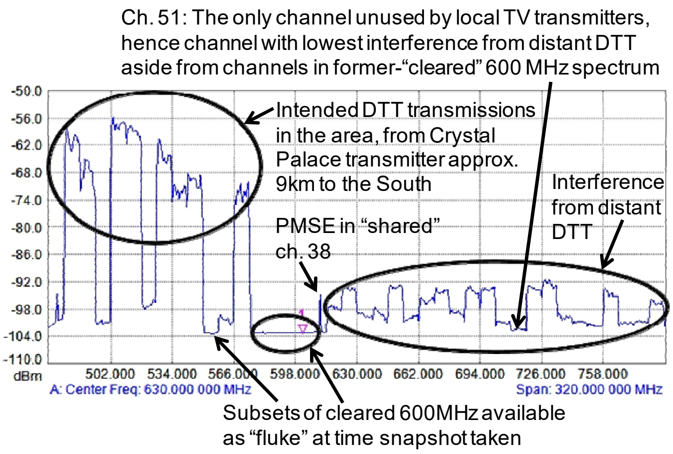


Fig. 1. A spectrum survey performed looking South from the King's College London Guys Campus hospital tower, clearly showing the intended TV transmissions covering the area, interference from distant DTT transmissions that are not meant to be covering the area, and other characteristics such as a PMSE device transmitting on the shared PMSE channel 38. Covers UK TV band (470-790 MHz), measuring dBm per 30 kHz, roughly calibrated.

B. *Transmission Power*

Another important consideration is the transmission powers of WSDs, noting that US and EU rules for WSDs limit them to a maximum of 36 dBm, or 4 W, EIRP [1], [3].

To understand the characteristics of the spectrum in which such systems are operating, it is important that these values are considered against TV transmission stations—which typically transmit at very high power. In the UK case, for example, certain transmitters are transmitting at 200 kW ERP or more on each single channel/multiplex they are using, with either horizontal or vertical polarization, or in some cases both. This is equivalent to 328 kW EIRP—almost 50 dB higher than a WSD's maximum EIRP in a best case scenario. Moreover, there is an intensive reuse of TV frequencies across much of the UK and in many other such deployments. This is by repeaters to enhance coverage, each transmitting on locally least-used channels. The result of this is that, in the UK case, all TV channels are very heavily used [5]—especially considering that each of the TV transmitters are transmitting typically on 6 and sometimes up to 9 channels/multiplexes. Moreover, the main transmitters use different sets of multiplexes in different locations, as the content varies locally. There is a similar situation, although not as severe, in many other European countries.

The UK case—the only current implementation of the EU rules—is assisted greatly by the locations of all victim TV or PMSE primary receivers being known due to TV receiver and PMSE licensing requirements. This greatly assists the framework in calculating the precise interference effects at particular receivers, and although the resulting complexity is high, it facilitates far more TVWS becoming available. In other cases, e.g., in the US where there is not such a precise knowledge of the locations of TV receivers, general assumptions have be made, such as the calculation of coverage bounds of TV transmitters, and limiting WSD transmission so as to not violate harmful interference limits at those bounds.

1) *Implications*

There are severe implications of the transmission power requirements on WSDs, and likewise of the transmission power characteristics of the primary systems (and particularly TV transmitters) in the area. The availability of TVWS is constrained in certain locations, e.g., with highly-variable transmission powers for WSDs under the EU rules, or is simply not usable at all in many locations (e.g., in big cities) under the US rules. This causes a great uncertainty in the quality of service that can be expected to match the characteristics of the deployment scenario, making certain scenarios more viable than others. QoS in some scenarios can be made more uncertain due to the interference from distant

TV primary transmitters being high. This is evidenced from the spectrum analysis reported in Figure 1, through which it is clear that interference from the distant TV stations that are not meant to be covering the area (even in channels for which the maximum transmission EIRP of 36 dBm is allowed under the UK/EU framework) can significantly reduce SINR.

This spectrum analysis was done with direct line-of-sight to the Crystal Palace TV transmitter at 8.8 km distance, where it is noted that all those channels below 534 MHz were transmitted at 328 kW (85.16 dBm) EIRP. The average TV signal strength of those channels below 534 MHz as represented in Figure 1 is around -61.25 dBm, not calibrated as it is not necessary to do so here for our purpose, and expressed in dB. A 4 W (36 dBm) WSD signal is 49.16 dBm lower in power than the 328 kW EIRP TV transmitter, and therefore would be received at -61.25-49.16 = -110.41 dBm if using the same configuration as Figure 1. This leads to even the lowest interference channel (Channel 51) in Figure 1, outside of the cleared 600 MHz channels which were unused as a "fluke" at the time this spectrum analysis was done, achieving only a SINR of less than -10dB for the WSD. This signal, which considering the additional 3.39 dB loss due to frequency difference, is unusable. Alternatively, in scenarios that are not affected by such interference, WSDs have been shown to perform well in transmissions of over 10km or more.

Hata Urban Large City modelling implies a loss of 115.72 dB over this distance and configuration (although with the receiver/mobile station height specified somewhat outside of the range of the Hata Urban model), so this would lead to the 1.23 kW (60.90 dBm) per 30 kHz Power Spectral Density (PSD) reducing to 3.30×10^{-9} W (-54.82 dBm). In comparison with the power levels seen below 534 MHz in Figure 1 which average at -61.25 dBm, this indicates a need for a correction factor of around 6.43 dB increase to the powers seen in Figure 1, due to calibration issues. Adjusting the Hata Urban Large City loss model to cope with the aforementioned 6.43 dB "calibration" difference with observed results in Figure 1, it can be shown that even in this best case Channel 51, the 36 dBm signal (0.02 W or 13.01 dBm per 30 kHz—assumed to have an actual transmission bandwidth of only 6 MHz, which is a reasonable assumption in a 8 MHz channel) could achieve a 0 dBm SINR at only 5.5 km transmission distance, a 10 dB SINR at only 2.6 km, and a 20 dB SINR at only 1.2 km. The interference situation is improved somewhat by lowering the receive WSD antenna such that it hears less of the interference from distant TV systems.

C. *Types of White Space Devices*

WSDs according to the US framework are classified as "fixed" or "personal/portable", whereas in the EU "Type A" and "Type B" WSDs are defined, respectively for fixed and non-fixed operation. Moreover, "personal/portable" devices can be classified as Mode 1 or Mode 2 in the US, whereas in the EU all WSDs are classified as either "master" or "slave". In fixed and Mode 2 personal/portable or master operation, the WSD obtains its information on TVWS availability directly from the geolocation database over the Internet, whereas in Mode 1 personal/portable or slave operation, the device obtains its information indirectly via a Mode 2 or master device. Moreover, Mode 1 and Mode 2 in the US apply only to personal/portable devices, whereas in the EU master and slave operation are not constrained to types of devices.

Types A and B in the EU relate to the types of antennas fitted to the devices in addition to their mobility, the latter only being able to use "dedicated" antennas (i.e., those only possible to fit to the specific devices, e.g., with a custom connection) and "integral" antennas (i.e., part of the device, not removable) [3]. However, in the US case, there are additional power limitations for personal/portable devices, being constrained to only 100 mW EIRP. Fixed devices in the US are constrained to 4 W EIRP; the power output from the WSD radio is constrained to 1 W, with the difference to 4W being achieved by antenna gain. If the antenna gain is higher, the power output from the WSD radio must be reduced accordingly.

1) Implications

The use of personal/portable devices in the US limits them to relatively shorter-range applications or cases where there is a high antenna gain at the receiver, increasing coverage distance, whereas the use of Type B devices in the EU has lesser implication, simply reducing flexibility in antenna design. The use of slave devices in the EU means that they must have some form of connectivity to a master device to achieve access. This naturally leads to an infrastructure-based network with masters acting as "hubs" connected to the Internet in a "hub and spoke" layout; however, the fact that "slave" devices can communicate directly with each other does allow the spokes to be extended over multiple hops or for other network structures to potentially form. The situation in the US leads to likely similar network structures; although the personal/portable devices can communicate with each other by design in that case, the 100 mW EIRP limitation again constrains the range of such communication.

The use of spectrum sensing only devices in the US opens up more scenarios for their deployment, however, the PSD limit of such devices likely means that they will only be able to operate in short-range and low-power scenarios, such as for body-area and personal-area networks. There are also challenges with antenna design in such scenarios, as covered in Section II.F.

D. *Transmission Spectral Masks*

There are two different approaches to transmission masks in the US and EU. In the US, the transmission mask is fixed, simply specifying a requirement of fixed PSDs limits in the intended and adjacent (and further out) channels, equivalent to a 55 dB difference. The EU approach specifies five different spectrum mask classes [3], with different mask requirements in channels up to three from the intended channel, comparing the 8 MHz intended channel with 100 kHz chunks in adjacent channels. This is already 19 dB lower, meaning that the second toughest spectrum mask class (Class 2, -74 dB across all non-transmission channels distances) is equivalent to the -55 dB case in the US in terms of like-for-like PSD. The toughest spectrum mask class in the EU case is the same as the US case in the adjacent channel, with increasing limits up to 10 dB tougher in the further out channels. Class 3 in the EU case is quite similar to an LTE transmission mask (in the adjacent channel, -64 dB, 10 dB more lenient than the US case and the toughest EU cases), whereas Classes 4 and particularly

Class 5 are very relaxed. All classes in the EU case have a floor to the out-of-band emission requirement of -84 dBm/100 kHz, below which it is not necessary to further limit out-of-band emissions.

1) Implications

Transmission spectrum masks in the US are tough, tougher than LTE by 10 dB. This is one factor leading to devices being relatively expensive and most appropriate for something of a niche market. In the EU case, there is a lot more flexibility with the 5 defined spectrum mask classes, allowing for a good trade-off between the performance in terms of allowed EIRP, and device cost.

E. License-Exempt vs. Licensed Spectrum Access

It is noted that both the US and EU frameworks allow access to TVWS on a license-exempt basis, with the responsibility for correct operation of the framework and correct parameterzation of the WSDs being at the certification/manufacture stage through ensuring conformance with the framework (e.g., only being able to transmit after checking with the database and setting parameters accordingly, implementing a “kill switch”, etc.). This is with the rare exception of the UK case where access is on a licensed basis for manually-configurable WSDs.

For such license-exempt access in general, and particularly within the constructs of the US and EU TVWS frameworks, the license-exempt devices access the available resource as they choose, e.g., in terms of the chosen channels and EIRPs (as long as complying with the framework), their MACs, (possible) multiple access schemes and PHYs, etc. There is no coordination among the devices, except, for example, in the context where they all apply the same standard or group of standards and that standard has a coordination mechanism incorporated (e.g., CSMA in the case of 802.11, inter-cell coordination in the case of 802.22, etc.).

1) Implications

The license-exempt access implies uncontrolled interference among WSDs, with no regulatory plans to change that situation even though the US and particularly the EU framework could manage such interference among devices should it wish to, with relatively minor changes. The situation is compounded by the presence of multiple standards and proprietary designs on the market, meaning that the interference among such devices is uncontrolled, although it is noted that some of them will attempt to improve the situation by sensing the interference level before choosing which TV channel to use (while obeying allowed channels and powers).

F. Antennas

A final characteristic of TVWS is the size of antennas in such cases. Wavelengths at these frequencies vary from 0.38 m to 0.63 m. Antennas must therefore usually be relatively large, depending on directionality and gain requirement. Omnidirectional antennas can be relatively small.

1) Implications

Often it is the case that only in fixed scenarios where large, e.g., Yagi antennas can be used that WSDs operate under the full potential of TVWS rules. Smaller devices will have a lower gain or efficiency, and in the US fixed WSD case for example, would be challenged to extract maximum EIRP.

TABLE I: SCENARIO CONFIGURATIONS

	Transmitter Height (m)	**Required EIRP (dBm)**
Configuration 1	30	>=30
Configuration 2	1	>=20

III. PERFORMANCE ASSESSMENT

In this section, we assess the performance that TVWS can achieve in various scenarios. This work is based on queries of a real database operating within the UK framework (which is, of course, under the EU Harmonized Standard hence being applicable to the EU in general), achieved by adapting some aspects of a WSD created at King’s College London built on Eurecom software radios and waveforms [7].

The two scenarios we consider are given in Table 1, where Configuration 1 represents the downlink of a mobile broadband system or a high power fixed link, among other use cases. Configuration 2 represents the uplink of a mobile broadband system, wireless indoor local-area networking, or femto-cell deployment, among other use cases.

All results are taken for the London “M25” area, over an area of approximately 53 by 40 km (2,120 km^2). Results are taken sampling and processing channel availability every 0.01 degrees both in latitude and longitude, making 2,775 measurement across the entire area for each assessment. For a (at least reasonable capacity) mobile broadband signal, we assume a transmission bandwidth of 20 MHz, requiring three contiguous 8 MHz channels to be aggregated. We assume the same bandwidth for a reasonable capacity wireless indoor local-area networking link. We also consider futuristic uses where we study performance for bandwidths of up to 160 MHz being aggregated (20 channels of 8 MHz), and cases where the spectrum might be aggregated discontinuously as could be achieved, for example, by a novel Filter-Bank Multi-Carrier (FBMC) 5G waveform.

Referring to results in Figures 2 and 3 and Table 2, it is clear that Configuration 1 has a questionable performance on the downlink in terms of dependability in aggregating sufficient TV channels for a mobile communication signal (20 MHz, three contiguous channels); if the aggregation is reduced to only two contiguous channels (e.g., supporting a 10 MHz mobile signal) confidence is increased from around 60% (varying marginally dependent on class) to over 98% for Classes 1-3. The confidence is over 99% if the aggregation requirement is removed. Configuration 2 performs excellently almost throughout. This configuration achieves over 99% confidence in having three contiguous channels for all classes, and over 95% confidence (97% for Classes 1-4, 96% for Class 5) in having 6 channels available (allowing a 40 MHz signal, along with good side-bands for protection of adjacent channels). This performance is so good that it is meaningless mapping the performance for 3 contiguous channels, as only one location in the entire London area failed to aggregate three contiguous channels: this was that at the Strand in Central London, given local theatre productions and PMSE usages. We have instead mapped availability for 20 contiguous channels in Figure 2(b). Even for such a high contiguous bandwidth, equating to 160 MHz, the confidence in these contiguous channels being available is over 83% for all spectrum mask classes. Finally, one key fundamental observation from our work has been that when aggregating three or more contiguous channels under Configuration 1, all spectrum mask classes perform almost identically. All spectrum mask classes perform identically when aggregating any number of contiguous channels in Configuration 2 [6].

Other results, not included here due to space constraints, indicate that if aggregating channels non-contiguously under Configuration 1, there is over a 97% confidence in achieving the three sufficient channels for a 20 MHz signal under Classes 1-3 (over 99% for Class 1, 98% for Class 2), with Classes 4 and 5 dropping to 89% and 82%. Under Configuration 2, this time aggregating 6 channels non-contiguously (for 40 MHz bandwidth), there is 99.9% confidence for Classes 1-4, and over 99% confidence for Class 5. Even aggregating 20 channels non-contiguously (160 MHz), there is over 93% confidence for Classes 1-3, 90% for Class 4, and 87% for Class 5. A further observation is that for both configurations, Classes 1-3 generally perform reasonably similarly, with minimal gain achieved by striving for Classes 1 and 2, noting again that Class 3 is close to LTE in terms of adjacent channel emission requirements [3].

IV. Inferences for TV White Space Use Cases

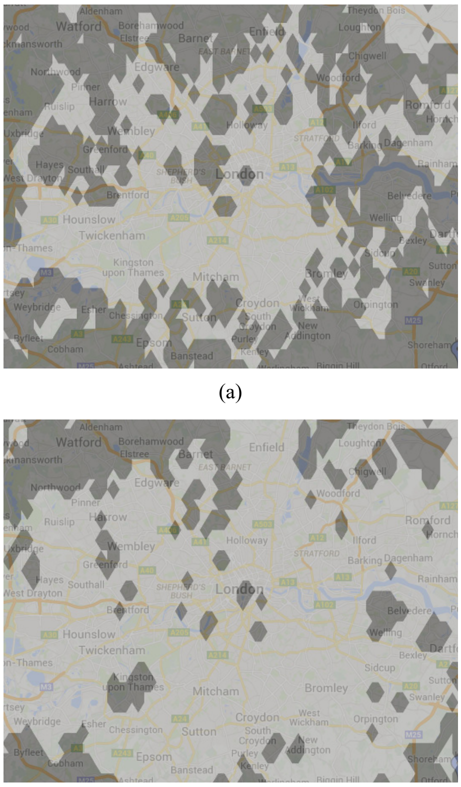
In this section, based on the characteristics expressed in Section II and the extensive practical work and associated experience of our trial some of which is described in the performance assessment of Section III, we provide observations on appropriate use cases for WSDs under the US and EU frameworks, and in various scenarios internationally.

A. Network Type and Structure

Based on the observations in the prior section, it seems likely TVWS will be deployed primarily in conventional network structures where you have a base station or access point with Internet access, and terminal that is connecting wirelessly to that base station or access point of TVWS, or in scenarios where the aim is to achieve a fixed link or number of fixed links with one end having Internet access and the other end not. This type of deployment is anyway consistent with the vast majority of deployment cases in general for wireless communications. It seems likely that WSDs may also be used for low-power short-distance networks, such as PANs and BANs, or low power relatively low data rate large-scale command and control applications (e.g., industrial wireless). These aspects are particularly facilitated in the US through the use of sensing-only WSDs.

B. Deployment Scenarios

Given the above observations, and given our further testing, it seems likely that TVWS is most appropriate for cases where the receive radio is either below rooftop or otherwise relatively well shielded from interference sources, e.g., in valleys, or indoor/underground. This is particular the case if the intended receive power is relatively low (e.g., long-distance links). Of course, there are challenges for indoor and underground deployment, however, for at least the meantime, manually-configurable WSDs (with manually entered geolocation information) are allowed in the UK, assisting such



(a)

(b)

Fig. 2. Locations where a given number of contiguous channels can be aggregated (darker areas indicate aggregation not possible): (a) Configuration 1, 3 contiguous channels, (b) Configuration 2, 20 contiguous channels.

TABLE II: Number of channels available for contiguous aggregation

	Required confidence (%)	Class 1	Class 2	Class 3	Class 4	Class 5
Configuration 1	99	1	1	1	0	0
	98	2	2	1	0	0
	95	2	2	2	1	0
	90	2	2	2	1	1
	75	2	2	2	2	2
	50	3	3	3	3	3
	25	11	11	11	10	9
Configuration 2	99	3				
	98	4				
	95	7				
	90	8				
	75 and below	20				

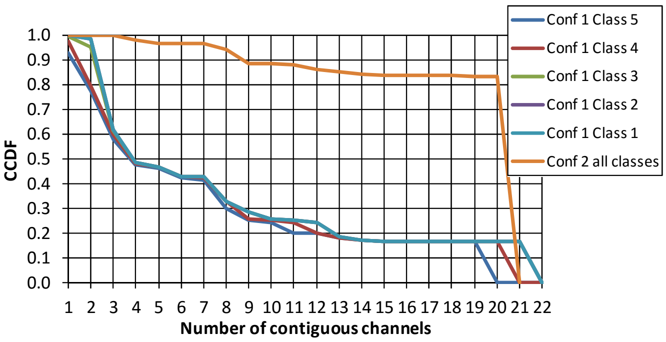


Fig. 3. CCDFs of number of channels available for contiguous aggregation.

indoor or underground scenarios. As explained in Section II.B and Figure 1, it is already observable that interference from primary systems in TV bands makes some particular scenarios highly challenging, and the interference among WSDs as they become more and more widely deployed will make the situation significantly worse.

Table III provides observations on scenarios for the EU case, where the reasoning here is quite self-explanatory given prior discussion. Concerning the US case, it is anticipated that TVWS is most appropriate in low spectrum usage scenarios, away from big cities. For example, TVWS might be most successfully used for broadband provisioning in rural areas through standards such as IEEE 802.22 or proprietary fixed link systems, or for very low power scenarios (PANs, BANs, short-range IoT, etc.). However, there are some current deployment examples in the US which are covering alternative cases, such as provision of white space access within small-to-medium sized cities, or in university campuses.

It is noted that many of the other deployments worldwide are providing Internet access to sparse remote conurbations or equipment, similar to the types of cases in which TVWS is most beneficially used in the US. The vast majority of such deployment examples internationally are in locations where white space is readily available, concurring with our observations on deployment scenarios under the US framework and using the US rules.

V. Conclusions and Important Future-Proofing Observations

This paper has analyzed use cases for TVWS, based on real practical experience from a major trial within the Ofcom TV White Spaces Pilot.

It is noted that Ofcom has in February 2015 issued a statement approving of TVWS usage in the UK [8]. That same statement outlines some planned refinements to the framework, which for the most part can be read as tightening up of protection for primary services. Although this implies a reduction in white space availability and capacity, it is anticipated that the broad observations provided in this paper will remain the same. Moreover, it is our understanding that Ofcom is further planning to adapt such assumptions (likely progressively reducing their severity—to something closer to the conditions when the work was done in this paper) as long as interference is not occurring in the commercial roll-out of white space technology and devices. Ofcom also aims to improve the situation through better modelling of aspects such as propagation in TVWS, thereby allowing increased EIRPs.

Concerning the US case, it is noted that the US 600 MHz incentive auctions is a big cause of uncertainty, at least until March 2016 which seems likely to be the month that the auctions will take place (or at least start).

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Table III: Anticipated performances of TVWS use cases in Europe

Deployment type	**Class range**	**Average performance**	**Certainty in performance**
Mobile broadband downlink	1-3	Good	Poor
	4-5	Average	Very poor
Mobile broadband uplink	All	Excellent (if base station mostly below rooftops in area, and as long as not too low intended Rx power)	Excellent
Short distance fixed links	1-3	Good	Poor
	4-5	Average	Very poor
Long distance fixed links	1-3	Average	Poor
	4-5	Poor	Very poor
Narrow band fixed links (e.g., smart grid), only using one TVWS channel	1-3	Excellent (if receiver mostly below rooftops in area, and as long as not too low intended Rx power)	Very good
	4-5	Very good (if receiver mostly below rooftops in area, and as long as not too low intended Rx power)	Average
Indoor wireless (e.g., femto, WLAN)	All	Exceptional	Exceptional
Novel 5G waveform (discontiguous aggregation) downlink	1-3	Excellent	Excellent
	4-5	Very good	Very good
Novel 5G waveform (discontiguous aggregation) uplink	All	Exceptional (if base station mostly below rooftops in area, and as long as not too low intended Rx power)	Exceptional
BAN/PAN or low power IoT communication	All	Exceptional	Exceptional

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